Application of the Virtual Fields Method to Reconstruct Full-Field Surface Pressures During the Dynamic Response of Blast Loaded Steel Plates

Rene Kaufmann[1,2,a], Sindre Nordmark Olufsen[1,2], Egil Fagerholt[1,2], Vegard Aune[1,2]

[1]*Structural Impact Laboratory (SIMLab), Department of Structural Engineering, NTNU - Norwegian University of Science and Technology, NO-7491 Trondheim, NORWAY*

[2]*Centre for Advanced Structural Analysis (CASA), NTNU, NO-7491 Trondheim, NORWAY*

[a]*rene.kaufmann@ntnu.no*

Abstract. This study presents an approach for the reconstruction of blast loading distributions from full-field deformation measurements on flat steel plates using the Virtual Fields Method (VFM). Both physical and virtual experiments are used to investigate the capabilities of the approach. Surface pressures in blast tests are commonly measured using load cells and pressure transducers, which can be intrusive and only provide point-wise information. Based on the principal of virtual work, the VFM allows the reconstruction of full-field surface pressure distributions from surface deformation information instead. These can be obtained using non-intrusive, optical techniques. Results from virtual and physical experiments are shown here to demonstrate the potential of the proposed approach.

Introduction

Physical tests are frequently carried out to obtain more insight into the dynamic response of blast loaded structures. This insight can be used to improve the design of protective and resilient structures. Both structural behaviour and blast-structure interactions occurring during such loading events are subject to current research [1] [2] [3]. The present study focuses on the reconstruction of dynamic surface load distributions during blast loading events from full-field deformation measurements using the VFM [3]. The VFM is an application of the principal of virtual work and was originally developed to extract material constitutive parameters from full-field deformation measurements. It has recently been used in several studies for the reconstruction of surface loads [*e.g.* 4, 5]. This study presents load reconstructions from experiments using deflectometry measurements during blast loading of a flat steel plate in pure bending. Further, results of simulated experiments are presented to demonstrate the potential of the method and to point out the challenges in practical applications for future studies.

Approach. For the first part of the study, a deflectometry setup for surface deformation measurements was installed in the dump tank of the SIMlab shock tube facility [6]. Shock tube exit blockages were used to generate different blast wave symmetries. Deflectometry uses a specular reflective specimen surface to record the reflected image of a periodic spatial signal, here a cross-hatched grid with a printed pitch of 5.9 mm. A high-speed camera (Phantom v2511) was used to record images at 75 kHz and to measure changes in the specimen surface slopes.

This technique is sensitive to vibrations, such that its application in a shock tube is challenging. A rigid frame connecting camera, grid and plate was used to address this issue. A steel plate with 30 cm side length and 5 mm thickness was used as specimen. The plate surface was polished to mirror finish to provide the required specular reflective surface.

For the second part of the study, the physical experiments were simulated in a virtual lab using finite element simulations to generate input for the load reconstruction analysis. Deformations were simulated using Abaqus Explicit and artificial grid deformation. The input pressure was based on transducer measurements to obtain realistic plate deformations. The modelled deformations were used to calculate artificial grid images as described in Ref. [5]. The grey noise level measured during physical experiments was added to the artificial grids, assuming a Gaussian noise distribution. This allowed simulating the image recording process and random error effects during pressure reconstructions. The simulated, noisy grid images were used as input for the phase detection algorithm used in deflectometry.

Load reconstruction. Surface pressure can be reconstructed for a thin plate in pure bending assuming homogenous material properties using the following expression:

$$\int_S \boldsymbol{\kappa}^* \cdot \boldsymbol{D} \cdot \boldsymbol{\kappa}\, dS + \rho\, t \int_S \boldsymbol{w}^* \boldsymbol{a}\, dS = \int_S \boldsymbol{p} \cdot \boldsymbol{w}^* dS \quad , \tag{1}$$

where $\boldsymbol{D}$ is the bending stiffness matrix, t the plate thickness and ρ the material density, all of which are known *a priori*. The curvature $\boldsymbol{\kappa}$ and acceleration $\boldsymbol{a}$ are obtained by processing the slope maps obtained from deflectometry measurements [5]. $\boldsymbol{\kappa}^*$ and $\boldsymbol{w}^*$ are the virtual curvatures and deflections which must be selected. Here, Hermite 16 shape functions are used for this purpose [3]. Virtual fields are defined over subdomains in this study, and pressure is identified iteratively over the entire surface.

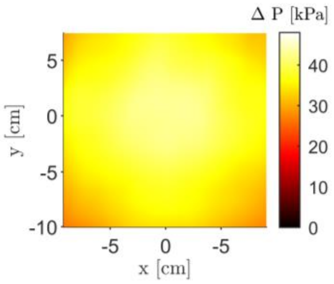

Figure 1: VFM pressure reconstruction from physical deformation measurements for peak pressure time instance.

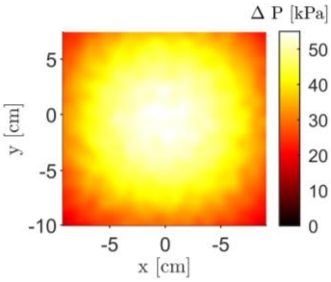

Figure 2: VFM pressure reconstruction from virtual experiment for peak pressure time instance.

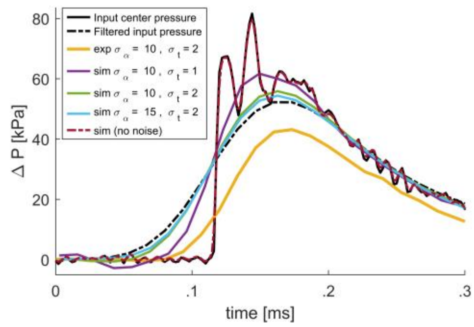

Figure 3: Comparison of pressure histories at the center of the plate for transducer measurements, physical (exp) and virtual experiments (sim).

Results. Fig. 1 shows the VFM pressure reconstruction from the measured deformation data. Fig. 2 shows the same reconstruction from deformations from the virtual experiment. Fig. 3 shows the pressure history from the virtual experiment at the center point of the plate. The transducer measurement data used as basis for the simulation are shown as reference. The figure shows that in the absence of added random noise, the methodology performs well on simulated data and captures the simulated peak amplitude with an accuracy of 98% (red dashed line in Fig. 3). It should be noted that amplitude reduction due to the 5-point central difference differentiation scheme in time is likely the main reason for the remaining inaccuracy. To compare virtual to physical experiments, the camera integration time and recording frequency are considered. These factors lead to a reduction in observable peak amplitude in both physical and virtual experiments. Transducer data were integrated and filtered in time the same way as full-field data to allow a comparison (black dashed line in Fig. 3). A Gaussian 3D-filter was applied to full-field data with temporal kernel size denoted σ_t and spatial kernel σ_α. The reconstructions of virtual data show good agreement with processed transducer data for appropriate filter kernel sizes. The experimental pressure reconstruction amplitudes are approximately 15% lower than those reconstructed from virtual data (yellow line in Fig. 3). This indicates the presence of experimental systematic error sources.

Conclusion

The present study on VFM pressure reconstruction for blast wave impact on flat plates shows that the proposed method can capture surface pressure distributions with both high spatial and temporal resolution. The simulated experiments revealed that the main limitations are low camera frame rates at high spatial resolution, random noise and experimental systematic error. Vibrations and limited capabilities in capturing acceleration accurately from slope data due to unknown boundary conditions were identified as a likely error source. Overall, the approach is found a valuable complement to existing blast wave pressure measurement techniques due to its ability to capture full-field, time-resolved pressure information.

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